Transversity and Meson Photoproduction

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Both meson photoproduction and semi-inclusive deep inelastic scattering can potentially probe transversity in the nucleon. We explore how that potential can be realized dynamically. The role of rescattering in both exclusive and inclusive meson production as a source for transverse polarization asymmetry is examined. We use a dynamical model to calculate the asymmetry and relate that to the transversity distribution of the nucleon.

The leading twist transversity distribution $h_1(x)$ [1] and its first moment, the tensor charge, are as fundamental to our understanding of the spin structure of the nucleon as are the helicity distribution and the axial vector charge. Unlike $g_1(x)$, though, the chiral odd $h_1(x)$ cannot be accessed in deep inelastic scattering. However, $h_1(x)$ can be probed when at least two hadrons are present, *e.g.* Drell Yan [2] or semi-inclusive deep inelastic scattering (SIDIS). In the latter process at leading twist, the effect of quark transversity can be measured via the azimuthal asymmetry in the fragmenting hadron's momentum and spin distributions. For spinless hadrons the so-called Collins asymmetry [3] depends on the transverse momentum of quark distributions in the target and fragmentation functions for outgoing hadrons [4]. Including transverse momentum leads to an increase in the number of leading twist distribution and fragmentation functions and can involve T-odd quark functions [5].

Non-zero transverse single spin asymmetries (SSA) have been measured at HERMES and SMC in semi-inclusive pion electroproduction [6]. These data could point to the essential role played by quark transverse momenta and T-odd distributions. Recently, further insight into transversity has come from the interpretation of deeply virtual Compton scattering (DVCS) [7] where the quark target helicity flip amplitudes, written in terms of the generalized parton distributions (GPD) $H_T^a(x,\xi,t)$, reduce in the forward limit to the ordinary transversity distribution, $\delta q^a(x)$. Angular momentum conservation in these amplitudes requires that helicity changes are accompanied by a transfer of 1 or 2 units of orbital angular momentum, highlighting the essential role played by the k_T generalizations of the quark transversity distribution. The $t\to 0$ limit of the associated form factor is the tensor charge.

This interdependence of transversity on quark *orbital* angular momentum and k_T is more general than the GPD analysis of transversity. This behavior arises in ref. [8] where we study the vertex function associated with the tensor charge. Again, angular momentum conservation results in the transfer of orbital angular momentum $\ell = 1$ carried by the dominant $J^{PC} = 1^{+-}$ mesons to compensate for the non-conservation of helicity across the local vertex. Transverse momentum dependence arises from the axial vector mesons that dominate the tensor coupling. [2] These mesons are in the $(35\otimes\ell=1)$ multiplet of the $SU(6)\otimes O(3)$ symmetry group that best represents the mass symmetry among the low lying mesons. Along with axial vector dominance this symmetry results in the isoscalar and isovector contribution to the tensor charge

$$\delta u-\delta d=\frac{5}{6}\frac{g_A}{g_V}\frac{M_{a_1}^2}{M_{b_1}^2}\frac{\langle k_\perp^2\rangle}{M_N M_{b_1}},\ \delta u+\delta d=\frac{3}{5}\frac{M_{b_1}^2}{M_{h_1}^2}\delta q^v.$$

Each depends on two powers of the average in-

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[2] C-odd axial vector mesons – $h_1(1170)$, $h_1(1380)$ and $b_1(1235)$

trinsic quark momentum $\langle k_\perp^2 \rangle$, because the tensor couplings involve helicty flips that require kinematic factors of 3-momentum transfer.

The $k_\perp$ dependence can be understood on fairly general grounds from the kinematics of the exchange picture in exclusive pseudoscalar meson photoproduction. For large s and relatively small momentum transfer t simple combinations of the four helicity amplitudes involve definite parity exchanges. The four independent helicity amplitudes can have the minimum kinematically allowed powers,

$$f_1 = f_{1+,0+} \propto k_\perp^1,\ f_2 = f_{1+,0-} \propto k_\perp^0,$$
$$f_3 = f_{1-,0+} \propto k_\perp^2,\ f_4 = f_{1-,0-} \propto k_\perp^1.$$

However, in single hadron exchange (or Regge pole exchange) parity conservation requires

$$f_1 = \pm f_4 \quad \text{and} \quad f_2 = \mp f_3$$

for even/odd parity exchanges. These pair relations, along with a single hadron exchange model, force f_2 to behave like f_3 for small t. This introduces the k_T^2 factor into f_2. However for a nonzero polarized target asymmetry to arise there must be interference between single helicity flip and non-flip and/or double flip amplitudes. Thus this asymmetry must arise from rescattering corrections (or Regge cuts-eikonalization or loop corrections) to single hadron exchanges. That is, one of the amplitudes in

$$P_y = \frac{2Im(f_1^* f_3 - f_4^* f_2)}{\sum_{j=1\ldots4} |f_j|^2}$$

must acquire a different phase. Rescattering reinstates $f_2 \propto k_\perp^0$ by integrating over loop $k_\perp$, which effectively introduces a $\left\langle k_\perp^2 \right\rangle$ factor [9]. This is true for the *inclusive process* as well, where only one final hadron is measured; a relative phase in a helicity flip three body amplitude is required.

Recently a rescattering approach was applied to the calculation of SSA in pion electroproduction, $ep \rightarrow e\pi X$, using a QCD motivated quark-diquark model of the nucleon [10] (BHS). In Ref. [11,12] the rescattering effect is interpreted as giving rise to the T-odd Sivers $f_{1T}^\perp$ function; the number density of upolarized quarks in a transversly polarized target. This function arises at leading twist in the SSA [13] in conjunction with the T-even unpolarized fragmentation function. Being T-odd, this asymmetry vanishes at tree level. The important lesson beyond the model calculation, is that, theoretically, final state interactions are essential for producing nonzero SSA's. Furthermore, the phenomenological determination of quark spin distributions can be disentangled from measurements of SSA's.

We have extended this approach to calculate the transversity distributions and corresponding SSA in SIDIS to access *transversity*. Collins [3] considered one such process, the production of pions from transversly polarized quarks in a transversely polarized target. The corresponding SSA involves the convolution of the transversity distribution function and the T-odd fragmentation function, $h_1(x) \star H_1^\perp(z)$ [13,14]. The analogous transversity distribution function can be defined through the light-cone quark distribution with gauge link indicated,

$$s_T^i \Delta' f(x, k_T) = \frac{1}{2} \sum_n \int \frac{d\xi^- d^2\xi_\perp}{(2\pi)^3} e^{-i(\xi^- k^+ - \vec{\xi}_\perp \vec{k}_\perp)}$$
$$\langle P|\overline{\psi}(\xi^-, \xi_\perp)|n\rangle\langle n| \left(-ie_1 \int_0^\infty A^+(\xi^-, 0) d\xi^-\right) \gamma^+ \quad (1)$$
$$\gamma^i \gamma^5 \psi(0)|P\rangle + \text{h.c.},$$

where e_1 is the charge of the struck quark and n represents intermediate diquark states. In the quark-diquark model this integral can be evaluated by integrating over q^μ, the gluon momentum (similar to the calculation in refs. [10–12]). We obtain

$$s_T^i \Delta f_T(x, k_\perp) = \frac{e_1 e_2 g^2}{2(2\pi)^4} \frac{1-x}{\Lambda(k_\perp^2)}$$
$$\times \left\{ \left(S_T^i \left[\left(m + xM \right)^2 + k_\perp^2 \right] + 2k_\perp^i \mathbf{S}_T \cdot \mathbf{k}_\perp \right) \right.$$
$$\times \frac{1}{k_\perp^2 + \Lambda(0)^2 + \lambda_g^2} \left(\ln \frac{\Lambda(k_\perp^2)}{\Lambda(0)} + \ln \frac{k_\perp^2 + \lambda_g^2}{\lambda_g^2} \right)$$
$$\left. - \left(S_T^i k_\perp^2 + 2k_\perp^i \mathbf{S}_T \cdot \mathbf{k}_\perp \right) \frac{1}{k_\perp^2} \ln \frac{\Lambda(k_\perp^2)}{\Lambda(0)} \right\},$$

where

$$\Lambda(k_\perp^2) = \mathbf{k}_\perp^2 + x(1-x) \left(-M^2 + \frac{m^2}{x} + \frac{\lambda^2}{1-x} \right).$$

The (Abelian) gluon mass (usually chosen at $\lambda_g \approx 1\ GeV$) is indicative of χSB scale and appears here to regulate the IR divergence.

The first part has the same nucleon spin dependent structure as a tree level model calculation [15] - it is leading twist and a combination of $h_{1T}(x, k_T)$ and $h_{1T}^{\perp}(x, k_T)$. The second part has a different structure than tree level - it appears as a rescattering effect only. It is IR finite and, in this model, is proportional to the one loop result for $f_{1T}^{\perp}$ [11] and $\mathcal{P}_y$ in BHS. The ratio of $h_{1T}(x, k_T)$ to $h_{1T}^{\perp}(x, k_T)$ will differ from the tree level. Integrating over k_T leaves $h_1(x)$. This one loop contribution constitutes the next order term in an eikonalization.

When combined with a measure of transversely polarized quarks, the fragmentation function $H_1^{\perp}(z)$, the integrated $h_1(x)$ ($h_{1T}(x)$ and the first moment of $h_{1T}^{\perp}(x)$) will contribute to the observable weighted meson azimuthal asymmetry from a transversely polarized nucleon [13,14]. Weighting by powers of k_T gives asymmetries in $\sin(n\phi_{meson})$.

The T-odd structure function $h_1^{\perp}(x, k_T)$ is of more interest both theoretically, since it vanishes at tree level, and experimentally, since its determination does not necessarily involve polarized nucleons [13]. Repeating the calculation above *without nucleon polarization* leads to the result

$$\begin{aligned} h_1^{\perp}(x, \mathbf{k}_\perp) &= \frac{e_1 e_2 g^2}{2(2\pi)^4} \frac{(m + xM)(1-x)}{\Lambda(k_\perp^2)} \\ &\qquad \times \varepsilon_{+-\perp j} k_{\perp j} \frac{1}{k_\perp^2} \ln \frac{\Lambda(k_\perp^2)}{\Lambda(0)}. \end{aligned}$$

This is again proportional to the $f_{1T}^{\perp}$ result. It is a leading twist, IR finite result. Being T-odd it will appear in SIDIS observables along with T-odd fragmentation functions. Many examples of such observables have been proposed, including SSA's, angular distributions of the final hadron and its polarization [13,16,17].

In summary, the Spin-flavor symmetry relates tensor charges to axial charges when supplemented with axial vector dominance. Secondly, axial vector dominance produces a $\langle k_T^2 \rangle$ factor that appears in rescattering models in meson photoproduction. Particularly, transversely polarized nucleon asymmetries in exclusive and inclusive π and η photoproduction are interference phenomena that require rescattering to be nonzero. This is true in SIDIS as well. The exchange picture for photproduction merges with the struck quark perspective when rescattering is effective.

The spectator model provides a testing ground for these notions and yields simple relations. Are they too simple? We are exploring several related issues. How to specify asymmetries precisely that will focus on the interesting distribution functions? What are the k_T dependences from different models? Are there more realistic intermediate states (that can carry spin information)?

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